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An analytical model for the motion of debris clouds induced by hypervelocity impact projectiles with different shapes on multi-plate structures

Qingtao Wang [a, b], Qingming Zhang [a, *], Fenglei Huang [a], Renrong Long [a], Zizheng Gong [c]

[a] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[b] Basic Education College of Commanding Officers, National University of Defense Technology, Hunan Changsha 410073, China
[c] National Key Laboratory of Science and Technology on Reliability and Environment Engineering, Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China

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ABSTRACT

An analytical model is presented in this paper for prediction of the motion of debris clouds induced by hypervelocity impact projectiles with different shapes on multi-plate structures. The debris cloud model is proposed for morphology, velocity distribution, mass distribution and damage effects on plates. The contour of first debris cloud is ellipsoidal and the others are ellipsoidal or spherical, depending on the impact condition. The equations for the debris cloud surface are obtained. It has been found that at a given time the velocity of the debris clouds is linearly distributed with respect to displacement, and the mass distribution is exponential along the impact direction. An example is given in detail, which shows that the model can successfully describe the motion of debris clouds produced by hypervelocity impact.

1. Introduction

The population of the orbital debris environment is continually increasing and this poses a serious threat to space-based assets. The protection of spacecraft against micro-meteoroids and man-made orbital debris is of a growing concern [1,2]. A variety of shields have been proposed to deal with these threats. Whipple shields consisting of two plates were employed in early times and lately have been evolved into multi-plate shields. In addition, with the kinetic energy weapon launch speed increasing, the damage ability also increases. It is the urgent need to evaluate the damage effect when the kinetic energy weapon hypervelocity impact the multi-plate. So the description of the first and the nth debris cloud is very important for spacecraft protection and kinetic energy weapon evaluation.

Hypervelocity impact multilayer structure is a typical process of large deformation of material, high temperature, high pressure and high strain rate. Generally it includes four stages, projectile impact the front plate stage; the first debris cloud formation, growth stage; debris cloud penetration the second plate stage; the second debris cloud formation, expansion and penetration the third plate stage; the following debris cloud formation and penetration the next plate stage. At present, a lot of research has been performed for debris cloud produced by hypervelocity impact. Swift [3], Piekutowski [4] and Bless [5] studied debris cloud theoretically and especially the characteristics of debris cloud produced by hypervelocity impact. Corvvonato and Destefanis [6] studied the debris cloud as a whole and proposed an integral model. Cohen [7] proposed a dynamic model of debris cloud. Recently, Long [9] proposed a model to describe the debris clouds produced by a hypervelocity impact projectile of spherical shape on the multi-plate shield. In this paper, a model is proposed to predict the debris clouds produced by a hypervelocity impact projectile with different shapes and on a multi-plate shield.

2. The first debris cloud model

2.1. Model description

The distribution of debris cloud, including materials of target and projectile, forms a kind of special geometrical surface which is not easy to find a function to define. The distributions of debris with different time show some geometrical similarity in space [6].

The debris cloud morphology formed by cylindrical projectile hypervelocity normal impact was simulated using AUTODYN6.1

* Corresponding author. Tel.: +86 1068915837; fax: +86 1068914284.

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Notations

Variable

V	velocity
L	length
d	diameter
x	axial coordinate
y	radial coordinate
t	time
ts	thickness of target
k_t	$1/t$
a,b	ellipsoid's long and short half axis.
θ	spread angle
h	distance
A,σ	model parameter
S_d	damage area
S	area
m	mass
ρ	density
E	kinetic energy
I	momentum
i	impulse per unit of area
C	sound velocity

Subscripts

p, t	projectile and target
n	number
f	the front and tail of the debris cloud
c	the center of debris cloud
dc	debris cloud
toushe	transmission

finite element program, the material of the projectile and target is aluminum. In order to save the computing resources, it can be simplified as a two-dimensional axisymmetric model for the whole model is axial symmetry. The projectile and target were simulated with the method of SPH (smoothed particle hydrodynamics), Gruneisen EOS (Equation Of State) and Johnson Cook [10] constitutive model. The particle shape is spherical, smooth radius is 0.25 mm. The material parameter is referenced from Ref. [11].

Fig. 1(a) shows the numerical simulation result for the morphology of debris cloud produced by an aluminum rod impacting an aluminum plate, with ratio of the rod length to diameter is $L/d_{\mathrm{p}} = 4$, $V_{\mathrm{p}} = 3.0$ km/s ($ts/d_{\mathrm{p}} = 0.4$). Fig. 1(b) is the corresponding density distribution of the produced debris cloud. Fig. 1(c) is the morphology of debris cloud produced by an aluminum rod impacting an aluminum plate, with ratio of length to diameter is $L/d_{\mathrm{p}} = 4$, $V_{\mathrm{p}} = 5.0$ km/s ($ts/d_{\mathrm{p}} = 0.4$) and Fig. 1(d) is the corresponding density distribution of the produced debris cloud. It can be seen from Fig. 1 that the debris cloud includes inner part and outer periphery part. The outer periphery part could be seen as an ellipsoid. All the mass, including the fragmentized material of target and projectile, is distributed on the surface of the ellipsoid. The inner part is the remaining of the projectile which is not fragmentized and lies in the front of the debris cloud.

In order establish an analytical model of debris cloud induced by the normal impact of a rod on a thin plate, the following assumptions are made:

(1) The structure of debris cloud includes inner structure and outer periphery structure.
(2) The periphery structure can be assumed as an ellipsoid, as represented by Fig. 2. The back vertex's velocity is zero and $V_{x,\max}$ is the front vertex velocity. $V_{y,\max}$ is the maximum expansion velocity in the y direction. $V_{\mathrm{c},1}$ is the velocity of the ellipsoid center.
(3) The inner structure is defined by the material parameters of the projectile, impact velocity and geometric features. When the projectile is not completely shattered, the periphery part of debris cloud includes the materials of both the remaining

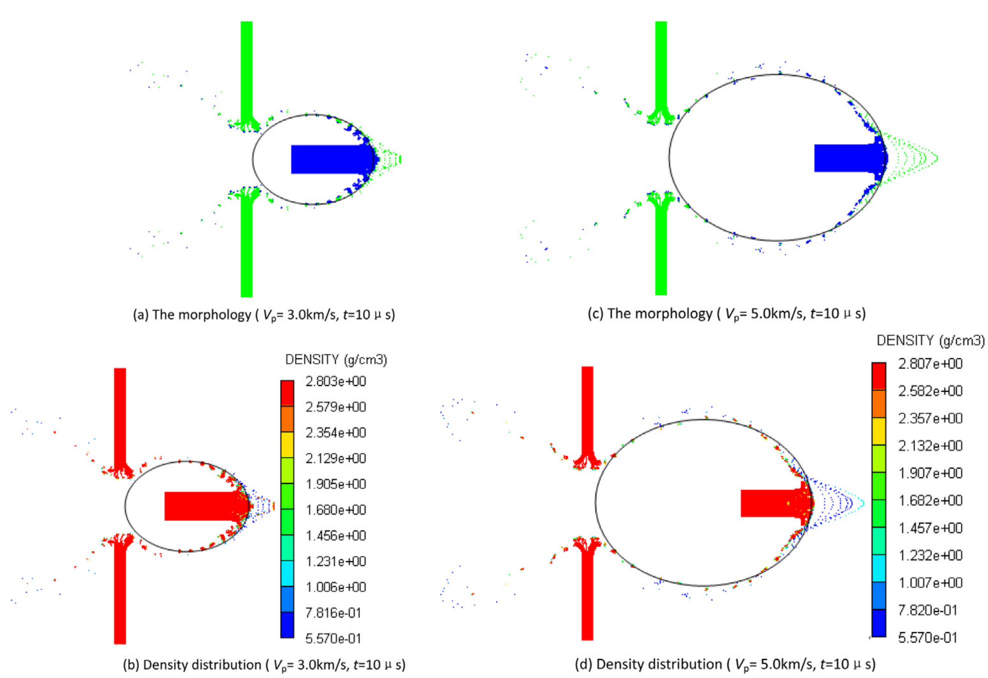

Fig. 1. The morphology of debris cloud produced by an aluminum rod impacting aluminum plate, as predicted by numerical simulation ($L/d_{\mathrm{p}} = 4$, $ts/d_{\mathrm{p}} = 0.4$).